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ORIGINAL RESEARCH ARTICLE

Application of water safety planning to improve drinking water safety in an Arctic community – a case study in Cambridge Bay, Nunavut

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ABSTRACT
Water safety planning is a risk management approach that accounts for quantitative and qualitative drinking water hazards and includes ongoing input from stakeholders. This approach has been applied in jurisdictions across the world including Canada. Rural and remote communities in Canada, impacted by water safety, stand to benefit most from holistic approaches to water safety risk management such as water safety planning. Unfortunately, these communities typically have limited resources to engage in this approach. Additionally, most remote communities rely on truck and cistern water systems, which have less understood hazards than communities in Canada with piped service. In this study, we report the results of an initial water safety planning case study in Cambridge Bay, Nunavut. We identified numerous water quality hazards including disinfection byproducts in trucks, manganese in the source water, and copper in tap water, as well as operational challenges that increase the risk of water emergencies in the community. We conclude that water safety planning has the potential to substantially improve water safety in Nunavut but current information gaps as well as complex stakeholder interactions are likely to hinder top-down attempts. A dynamic and inclusive approach is recommended that incorporates a targeted exploration of water safety hazards.

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Water quality; drinking water; water safety; Arctic water systems; Risk management

Introduction

The Territory of Nunavut is part of the Canadian Arctic and makes up one of the four regions of Inuit Nunangat [1]. All communities in Nunavut rely partially or entirely on decentralised truck and cistern drinking water distribution systems because of the cost and complexity of building and operating water piped networks in communities underlain by permafrost and that are subject to extreme cold temperatures [2]. Only limited drinking water quality data exists for most Nunavut communities [3], much of which has been collected by the territorial governments and some academic studies over the last 10 years. Past peer-reviewed studies have primarily examined microbiological water quality parameters in the Qikiqtaaluk and Kivalliq Regions [4–6] of Nunavut, as well as neighbouring Inuit-majority jurisdictions in Nunavik (Northern Québec) [7] and Nunatsaivut (Northern Labrador) [8,9]. In Nunavut, total coliforms have been found in both taps and cisterns in four of the communities, and *E. coli* in two communities [4,5]. In Nunavik, Martin et al. (2007) analysed household water cisterns in 4 communities, detecting total coliforms in 21 of 64 cisterns, but no *E. coli* [7]. Masina et al. (2019) found that untreated culturally significant surface water sources in Iqaluit contained *Giardia* (20.0%) and *Cryptosporidium* (1.8%) [6]. The authors determined that the public health risk to residents that consume these alternative sources was low but may increase over time due to climate change [6]. The exact percentage of Nunavut Inuit residents who consume untreated drinking water is unknown; however, Cassivi et al. (2024) found that 60% of Inuit residents surveyed inKangiqsualujjuaq, Nunavik relied on untreated water sources instead of tap water [10].

In contrast to the emphasis on microbiological parameters in previous studies and government policies, studies examining chemical water characteristics of treated drinking water in Nunavut have only been conducted in four communities [5,11]. However, a recent hydrocarbon contamination event in 2021 in Iqaluit has underscored the importance of monitoring chemical water safety hazards [12]. Chlorination, the only treatment applied in 10 of the 25 communities, targets microbial contamination, but does not remove metals, particulate matter, or most dissolved organic compounds [13]. For raw water, Elliot et al. (2022) provided an overview of the source water quality for all

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communities in Nunavut, with a case study on Sanikiluaq which experienced high salinity in the source water. It was hypothesised that the permafrost thaw allows for the defrosting of historic marine sediment salts that had frozen historically in the freshwater source [3].

Health Canada is the federal body that establishes the *Guidelines for Canadian Drinking Water Quality (GCDWQ)* that the provinces and territories in Canada can choose to adopt into regulation. In Iqaluit, Coral Harbour and Pond Inlet, Daley et al. (2018) found that the concentration of iron in samples taken from building taps was above the aesthetic objective (AO) set in the GCDWQ, and the AO for manganese was also exceeded in Pond Inlet [5]. In 2018 the AO for manganese was 0.05 mg/L, the new AO is 0.02 mg/L. Health Canada publishes revisions to the GCDWQ as new information becomes available and the AO's for iron and manganese have since been reduced [14,15]. As only percentages were provided in the Daley et al. (2018), it cannot be determined how many more buildings would now above the revised AO's or MAC in the communities. Similar AO exceedances for iron and manganese were found in Pond Inlet by Gora et al. (2020) throughout the water system in the months spanning from February to June 2018 [11]. The authors also reported a manganese concentration increase that exceeded the MAC (0.12 mg/L) during the winter months [11]. It was noted that this may attribute to oxygen depletion caused by the decomposition of organic matter in the lake during ice cover, which would affect the speciation of these metals. The high iron and manganese levels in the lake were then carried through the distribution system to consumers due to a lack of treatment barriers [11,16,17].

Water storage and exposure to plumbing materials can also impact on the biological and chemical aspects of drinking water safety. The control of bacterial growth in distribution infrastructure and domestic plumbing is improved by maintaining disinfectant residual throughout the system, reducing the natural organic matter (NOM) that enters the distribution system, and implementing corrosion control measures [18,19]. Multiple studies have reported incidences where chlorine residual levels were below the regulated concentration in the distribution system and/or below detection in domestic water storage tanks, increasing the risk of recontamination [20] in Nunavut [4,5], Nunavik [7], and Nunatsiavut [8,21]. Besides serving as a food source for microorganisms, NOM can combined with free chlorine can yield to disinfection byproducts (DBPs) [22,23], including species that are regulated in most jurisdictions in Canada such as trihalomethanes (THMs) [24] and haloacetic acids (HAAs) [25]. There is no MAC nor AO for NOM set in the Canadian guidelines [26]; however, in the US, the US EPA recommends an upper limit for total organic carbon (TOC), a measure of NOM, to be 2 mg/L for the prevention of THM formation [27].

Corrosion of domestic plumbing system components, which can lead to the release of metals like lead and copper, is a well-documented concern in non-Arctic municipalities [19,28,29]. In 2006, in Alaska, Hart and White (2006) undertook a study to examine metal corrosion in rainwater cisterns and found a correlation between collection material utilised and metal exceedances, however, there were no investigations focused on domestic cisterns in remote Arctic communities served by trucked distribution systems until 2017 [5,30]. Daley et al. (2018) found lead levels in random daytime grab samples that exceeded Health Canada's MAC (5 ug/L) and copper above the AOs in three communities. Gora et al. (2020) conducted a targeted follow-up study in Pond Inlet, using random daytime and sequential stagnation water sampling to test for heavy metals in plumbing and determine their sources buildings. Factors such as raw water quality, stagnation times, temperature, and disinfectant residuals [31] influence heavy metal release and biofilm formation, compromising treated water quality and facilitating pathogen proliferation [32–34]. Corrosion of iron-based distribution and storage components can also encourage the proliferation of microorganisms [35]; however, there is no evidence these components have been used in Nunavut.

Water safety planning and water safety risk assessment

Water safety plans (WSP) use a holistic approach to managing drinking water systems that was originally developed by the World Health Organization for use in low resource communities in the Global South (Figure 1). A WSP is often used as a prevention tool which incorporates both qualitative infrastructure information and quantitative water quality and operational data to support hazard identification and risk assessment. A risk score is calculated for each water safety hazard by multiplying a likelihood score by a consequence or score [36–38]. This score is then used to categorise the hazard as low, medium, or high risk using a predefined risk matrix. Water safety matrices have performed well in situations with scarce or unavailable data; however, there are limitations related to the precision of probability and impact estimations [39].

WSPs have been applied in Canada to improve water safety management, including a government-led initiative in Alberta and a pilot project in Atlantic Canada First Nations. In the latter case, Lane et al. (2022) co-developed

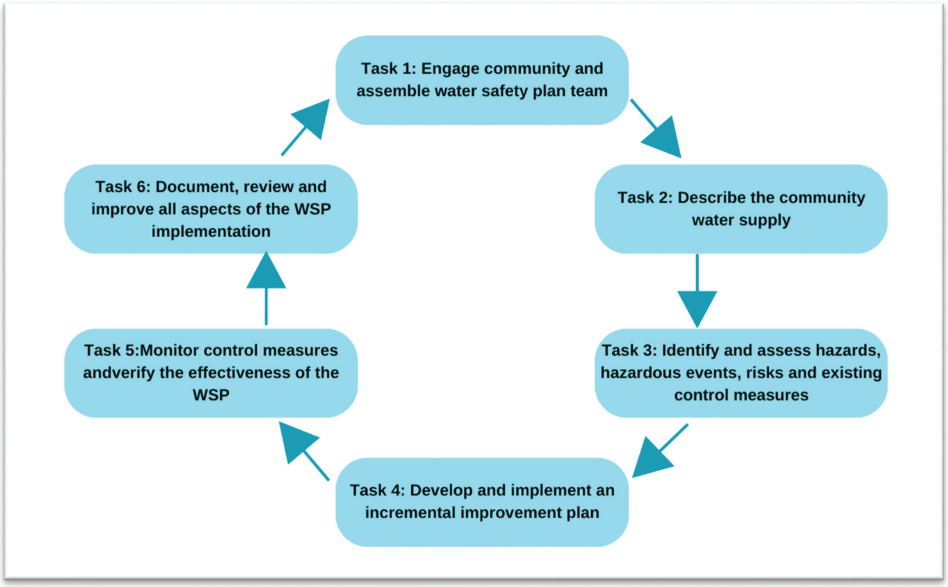

Figure 1. The water safety planning process as presented in WSP for small communities (adapted from [36]).

a risk assessment web application with First Nation stakeholders from six communities to build capacity for water safety management [40]. The study scope was limited to treatment and distribution hazards for individual systems and those common across the participating communities. Although increased communication and data ownership offered considerable benefits, Lane et al. (2022) found that operators viewed risk assessments as "strictly diagnostic" and were unlikely to include it in operational practice if it was "considered to not be required" [41]. The fragmented governance within First Nation means that adopting these proactive risk reduction strategies into regulation will require acceptance by multiple levels of government and a shift from focusing only on water quality monitoring [40].

Historically, only one study had reviewed the suitability and potential application of WSP in an Arctic context [42]. Recently, Chalmers et al. (2024) developed a WSP framework for Nunavut and proposed a new risk matrix constructed using the Cox Criteria [43], after determining that risk matrices criteria from other jurisdictions could not be directly applied to the unique factors found in Nunavut [2].

Cambridge Bay, NU

Cambridge Bay is located on the southern point of Victoria Island (Figure 2) and serves as the government, administrative, and transportation hub for Nunavut's Kitikmeot Region. It sustains a populace of nearly 2,000 individuals, not including visiting researchers to the Canadian High Arctic Research Station (CHARS). In 2017, CHARS was constructed by the federal government to encourage and facilitate northern research endeavours. This prompted upgrades to the water treatment plant and piped water distribution system in Cambridge Bay to accommodate the influx of people at the station and to comply with fire safety regulations. The community now has some of the most comprehensive water treatment infrastructure in the territory.

Objectives of this study

The objective of this study was to conduct a case study WSP for the community of Cambridge Bay, NU using the proposed water safety framework and risk matrix developed by Chalmers et al (2025). This study relied on findings from literature, the professional experience of the authors, and data provide by the Government of Nunavut [45]. The community's existing water quality data, design documents, and operational records [2] were analysed to find any temporal and location-based trends to establish gaps and to conduct a preliminary water safety risk assessments for Cambridge Bay.

The secondary nature of the data used in this study may have introduced human input errors, and inconsistent data collection in earlier years necessitated the removal of some data for meaningful statistical analysis.

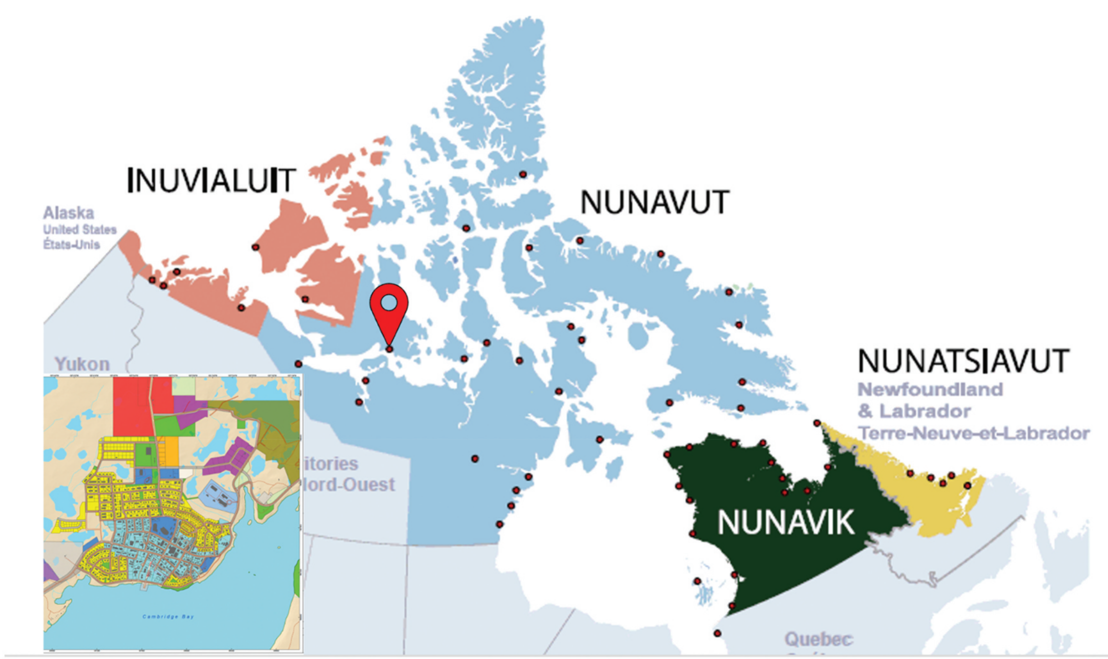

Figure 2. Map of the municipality of Cambridge Bay on Victoria Island [44] inuit Tapiriit Kanatami.

Positionality statement

The individual researchers who have authored this paper identify as settlers performing research at York University, Lassonde School of Engineering. Caroline and Elan have both worked/are currently working at Government of Nuanvut, Department of Community and Government Services (GN-CGS) in the roles of municipal support and senior municipal planning officer, respectively. Various written support has been provided to Caroline from from GN-CGS, the Municipality of Cambridge Bay and the Kitikmeot Heritage Society to undertake this research. This paper highlights hazards from the personal experiences of the authors and a review of literature.

Materials and methods

Description of Cambridge Bay drinking water system

Cambridge Bay's water system was initially constructed in 1970 as an intake pumphouse adjacent to the source "Water Lake" and has undergone several upgrades over the years, with the latest in 2017. The water delivery system comprises three 12,500 L water trucks, along with a spare, operating 7 days a week with a 10-hour work day. Additionally, there is piped water delivery that serves a limited number of facilities, including CHARS. The current water infrastructure includes a pumphouse at the water source with pre-treatment chlorine injection, a transmission line, and a treatment plant. The treatment plant consists of: filter feed pumps, raw water circulation pump, coagulant dosing (currently inactive), a pressure filtration system with three filters and backwash-holding tank, two UV reactors, a chlorine dosing system, treated water storage tank, truck fill pumps and core servicing pumps for the piped delivery [46] (Figure 3).

Cambridge Bay WSP case study

Identification of water safety hazards present in Cambridge Bay

Cambridge Bay was chosen as a case study because the available historical water quality data is extensive compared to other communities in Nunavut. A list of hazards relevant to Cambridge Bay was developed using the data, the water quality assessment report prepared for the Royal Canadian Mounted Police and the master list of hazards for communities in Nunavut developed by Chalmers et al (2025) [2]. The list was refined to include only hazards with documented occurences (Table 2) and excluded subjective opinion. Five hazards were then selected for detailed analysis using the Chalmers et al. (2025) WSP framework.

It should be noted that there could be additional information held by GN-CGS that requires Access to Information and Protection of Privacy (ATIPP) access to information. For this paper, we have included this in the table with a "yes – ATIPP required".

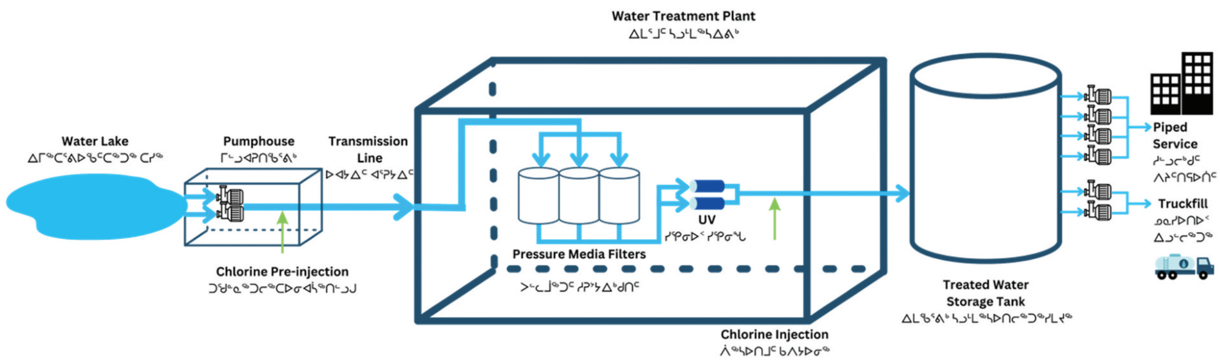

Figure 3. Schematic of Cambridge Bay water system.

Water quality data

The data used in this analysis was provided by GN-CGS via WaterTrax Data Management Platform. The chemical water quality parameters provided by GN-CGS included the general quality water analysis of pH, turbidity, organics, anions, cations, metals, hydrocarbons, as well as THMs and HAAs. No microbiological data has been reviewed as there have been no boil water advisories issued for the detection of E. coli in the water system from 2017 onwards [47].

Water quality data analysis

Prior to analysis, the data were reviewed for anomalies and cleaned, which included the grouping of sample location names. For example, "Lake" originated from different identifiers, such as CAM-01, WTP-01 and Water Lake. These disparate names were confirmed by GN-CGS staff to refer to the same location, thereby enabling the grouping of sample locations for statistical analysis and visualisation.

The dataset spanned from 2017 to 2023, with varying numbers of sampling events each year. To investigate annual and seasonal trends, the dataset was split into two subsets. The first subset covered the period from 2017 to 2023, focusing solely on spring freshet months (April, May, June) to identify any annual trends. The second subset encompassed the years 2022 to 2023 and included all sampling events, allowing for the examination of potential seasonal variations.

All water quality datasets were tested for normality to determine if the ANOVA or Kruskal–Wallis test should be used to identify any statistical significance for parameters between locations and between years at specific locations. Spearman's Correlation analysis was employed to assess the relationship strength between parameters. Attempts were made to conduct a Mann–Kendall test to detect seasonal water quality trends; however, due to limited data, these tests yielded inconclusive results. All data analysis was conducted in R using the tidyverse, dplyr and ggplot packages

Water safety risk

Water safety risk (R) is most commonly calculated as the product of the likelihood of a hazardous event occurring (L) and the resulting consequence (C):

$$R = L \times C \quad (1)$$

As described in the introduction and Chalmers et al. (2025) includes likelihood and consequence scores are assigned based on jurisdiction-specific criteria [2]. Likelihood criteria are often based on the past frequency or future probability of hazardous events and consequence scores are generally informed by local water safety regulations and/or the anticipated severity of health impacts (e.g. acute vs. chronic health effects).

Application of water safety planning to Cambridge Bay, NU

The Nunavut risk matrix proposed by Chalmers et al. (2025) includes likelihood and severity scoring criteria specifically tailored for Nunavut, an alternative weighted risk scoring equation, an risk scoring matrix that adheres to the Cox criteria, and a community-by-community approach to hazard identification that incorporates feedback from multiple stakeholders [2]. The scoring criteria took into consideration past frequency, existing treatment and operational barriers, existing regulations and practices, planned updates to regulations and practices [48], and the potential health impacts of different hazardous events.

The Nunavut risk matrix breaks the likelihood score into a system readiness score and an optional past frequency score. This reduces speculation and bias by using records of past events as well as evidence of barriers being in place to address the hazard [2,49].

$$Likelihood = xPF + ySR \quad (2)$$

where PF is past frequency, SR is system readiness, and x and y are weights assigned to each factor, where x and y add to 1. This likelihood score is then multiplied by the consequence score to determine the water safety risk score.

$$Riskscore = (xPF + ySR) \times C \quad (3)$$

Two of the proposed formulas for calculating the likelihood score were evaluated, one that considered only system readiness (RE1, $x = 0$, $y = 1$) and one that assigned a weight of 0.25 to past frequency and a weight of 0.75 weight system readiness (RE2).

Table S1 outlines the scoring criteria definitions along with risk equations that were proposed in Chalmers et al (2025). These equations are then applied to five hazards selected based on evidence of having occurred in Cambridge Bay.

Results and discussion

Identification of water safety hazards in Cambridge Bay

Past evidence of non-compliance with territorial or federal water treatment and operational guidelines in Cambridge Bay

Dillon Consulting [45] conducted a water quality assessment for the Royal Canadian Mounted Police in 2021, and identified that the water supplied did not meet the Canadian Drinking Water Quality Guidelines [13,50] (Table S2). The assessment, based on treated water quality data from 2018 to 2020, revealed THM and turbidity exceedances above the MAC, and aluminium and manganese concentrations above the AO, along with no detectable free chlorine residual within delivery trucks on 37 counts. The filtration system used in Cambridge Bay is a pressure filter, which is not included in Health Canada's list of recommended pathogen removal technologies [51]. Moreover, sampling results indicate that the filtration system is ineffective at removing particles and without a functioning coagulation system there is limited NOM removal, leading to THM exceedances.

Water safety hazards in buildings

Although the territorial and municipal government do not have any formal responsibility to monitor water quality in cisterns and domestic plumbing[52], the available literature suggests there is evidence that these systems can contribute to hazards [11,20], including:

- Microbiological contamination in storage cisterns
- Low chlorine residual in storage cisterns
- Continued formation of DBPs during onsite storage
- Lead and copper from premises plumbing in individual buildings

Characterising these hazards will require the participation of community members and stakeholders during sample collection as well as for validation. This may prove challenging as there are currently no water safety regulations or guidelines related to the design, installation, maintenance, or monitoring of cisterns and domestic plumbing in Nunavut and sampling only occurs on an ad hoc basis.

Other water safety hazards

A fuel spill near the source water intake was identified in Cambridge Bay by Dillion Consulting in 2021 and is further documented in the Northwest Territories Spill Database [45,53]. The fuel tank at the pumphouse has now been relocated to a minimum of 60 m distance from the source water and has been provided with an additional bunding to reduce the likelihood of spills contaminating the source water.

Water hazards observed in Nunavut communities in past academic studies, government reports, and consulting projects

Previous work by researchers, government scientists and engineers, and private consulting firms has identified numerous water safety hazards in Nunavut communities. Hazards that are potentially relevant to Cambridge Bay are summarised in Table 1 along with their potential causes.

Review of historic water quality data and identification of water quality safety hazards

ANOVA and Kruskal–Wallis tests were conducted to two main questions:

(1) Is there a variation in water quality across different points in the system (source, WTP, truck, cistern, tap) and does this vary over time, both seasonally and in the long term?
(2) Are there correlations between different water quality parameters?

Water quality from source to tap and over time

General water chemistry. Table S3&4 in the supplemental file list the averages, minimums and maximums for the general water quality parameters analysed in this study. In the source water, ANOVA analysis showed significant differences in pH and alkalinity (both $p < 0.05$)

Table 1. Identification and characterisation of water safety hazards that have been reported in the academic literature, government documents, and consulting reports in Nunavut and that could conceivably impact water safety in Cambridge Bay.

Location	Hazard	Potential causes (a.k.a. hazardous events)
Source Water	*E. coli* in source water [45]	Faecal contamination from wildlife and dogs in source water
	Cryptosporidium and *Giardia* in source water [5,6]	Faecal contamination from wildlife in source water
	Manganese in source water [3,11]	Naturally occurring, potential increase with permafrost thaw
	Iron in source water [11]	Naturally occurring, increase with permafrost thaw
	High turbidity [45]	Spring freshet, permafrost thaw
	Hydrocarbons in source water [45]	Recreational vehicles on or near lake in the winter could spill contaminants to watershed [45]
	Insufficient water supply	Increase water usage from population growth
	Access road [45]	Road to source, minor fuel leaks
	Fuel spill at intake [45]	Emergency generator leak and entering source
Water Treatment Plant (WTP)	*E. coli* in treated water [4,5]	Source water contamination, treatment failure
	THMs above guideline in treated water [45]	Excessive chlorine dose, presence of THM precursors
	Manganese in treated water [11]	Inefficient backwashing Use of incorrect media
	Iron in treated water [11]	Treatment failure
	Copper in treated water [5,11]	Corrosion in treatment plant plumbing
	Low chlorine residual in treated water [4,5]	Treatment failure Increased chlorine demand from source water turbidity (> 1 NTU) Upgrades in pipes and pumps impacting CT
	Turbidity [45]	Sediments in treated water storage causing recontamination
	Cryptosporidium and *Giardia* in treated water [54]	UV disinfection system not operating properly Not using LT2 1 micron cartridge filters
	Pump failure and repair	Power surge Lack of maintenance and asset management
	Inadequate water supply	Inefficient water pumping/truck delivery to meet supply and demand (open community Facebook group provides evidence of insufficient water deliveries) [55]
	Inadequate water supply	Pipe failure – heat trace fails, frozen transmission line and utilidor Lack of maintenance and asset management
	Manganese in distributed water [5,11]	Resuspension
	Iron in distributed water [5,11]	Failure or no coagulation
	Lack of water deliveries to community, low water availability	Truck failure and repair
	Aging infrastructure	Deterioration of treatment plant
	THMs above guideline in distributed water [11,45]	Excessive chlorine dose and presence of THM precursors
Utilidor	Aging infrastructure	Deterioration of distribution infrastructure
Trucks	Aging infrastructure	Lack of operator training
	THMs above guideline in distributed water [11,45]	Excessive chlorine dose and presence of THM precursors
	Road access	Blizzard prevents water delivery
	Low chlorine residual in truck [54]	Treatment failure Operators not trained Improper disinfection of trucks
	Lack of water deliveries to community, low water availability	Sick truck driver/on vacation/no cover
	E. coli in distributed water [4,5]	Treatment failure, improper disinfection of trucks
Water tanks	*E. coli* in distributed water [4,5]	Inadequately maintained tank/stagnation time
	General microbiological contamination	Disinfectant decay due to long stagnation time or tank hygiene
	Legionella in distributed water [5,56]	Stagnation of water in water cisterns
Taps	Copper in distributed water [5,11]	Corrosion of plumbing components
	E. coli in distributed water [4,5]	Improper cleaning around tap after food prep
	Lead in distributed water [5,11]	Corrosion of plumbing components

Abbreviations in Table 1.
WTP -Water Treatment Plant.
NTU – Nephelometric Turbidity Units.
THM – Trihalomethane.
CT – Contact Time.

between different sampling events. Additionally, ANOVA analysis revealed that there were significant differences in alkalinity ($p < 0.05$) in the source water across different years. Within the treatment plant, only turbidity showed a significant difference between the years ($p < 0.05$). Turbidity levels varied significantly in the trucks between March 2022 and June 2022 ($p < 0.05$) and March 2022 and June 2023 ($p < 0.05$). Parameters analysed in the trucks using ANOVA, showed significant differences in pH and turbidity ($p < 0.05$).

Table 2. Use of proposed approach to hazards that have evidence of being present in Cambridge Bay, Nunavut.

Hazard	Hazardous event	Past frequency	System readiness	Consequence	Risk score (RE1 & RE2)	Risk level
THMs in trucked water	Presence of THM precursors	2	4	4	16	High
					14	High
Copper in tap water	Corrosion of copper piping components	1	5	2	10	Moderate
					8	Moderate
Hydrocarbons in source water	Fuel spill	1	2	5	10	Moderate
					8.75	Moderate
Manganese in tap water	Natural manganese not removed via treatment	1	2	4	8	Moderate
					7	Moderate
Inadequate water supply to buildings	Aging infrastructure - breakdown of water truck	2	4	3	12	High
					10.5	Moderate

Lead and copper. Lead and copper release is influenced by the amount of time that the water has spent in contact with plumbing components (stagnation time) [18,19,57]. Lead is rarely detected in surface or groundwater supplies in Canada [57] and lead components are not used in water equipment or delivery trucks, so the presence of lead would likely be attributed to domestic plumbing systems. Only two samples were collected from buildings in Cambridge Bay, and neither of these samples exceeded Health Canada's MAC (5 ug/L). Historically public housing buildings across the territory are commissioned by Nunavut Housing Corporation [58] and were constructed by the same limited pool of contractors. Although no information is available on building-specific conditions in Cambridge Bay, it can be hypothesised that plumbing systems would be similar to those across the territory if the same contractor was used.

The MAC for copper set by Health Canada [18] is 2,000 ug/L with an AO of 1,000 ug/L. In 2017, non-routine regulatory samples were taken twice at the high school in Cambridge Bay, the exact location is unknown; however, samples showed significantly higher levels compared to samples from the lake, water treatment plant and trucks (Kruskal–Wallis $p < 0.05$). The elevated copper levels at the school align previously published findings. Daley et al. (2018) found that over 15% of their samples exceeded the AO for copper in the four Nunavut communities [5]. Gora et al. (2022) conducted a more comprehensive study in Pond Inlet identifying copper levels ranging from 51 ug/L to 3,915 ug/L in random daytime samples from various buildings [11]. While there is not enough data for Cambridge Bay to determine if copper leaching exists in other buildings, the minimal amount of copper found in the source water and water trucks suggest that the high school's copper levels stem from plumbing within the building (Figure 4). General water quality impacts and NOM are discussed in more depth below; however, it is apparent that further investigation is required to gain a proper understanding on what is causing the release of copper in the high school and potentially in other buildings as well.

Other factors that contribute to copper and lead release from building plumbing include general water quality impacts, natural organic matter, iron and manganese, and building-specific conditions [11]. It is known that pH lower than 7 and soft waters can cause corrosion [18]. However, pH levels from 2017 to 2023 remained within the range of 7.4 to 7.8, and the water in Cambridge Bay exhibits high alkalinity and hardness (>200 mg L $CaCO_3$) compared with communities in the Kivalliq and Qikiqtaaluk Regions, which all showed relatively low alkalinity [5]. This high alkalinity effectively maintains a stable pH throughout the distribution system for corrosion control [18]. High alkalinity groundwaters are known to be aggressive towards copper [59,60]. For instance, tap water samples from relatively new copper plumbing in large buildings yielded copper releases ranging from 1.4 to 2.4 mg/L in water with a pH of 7.4 and alkalinity of 273 $CaCO_3$ mg/L. Similarly, Schock and Fox (2001) reported that in water with a pH of 7.3 and alkalinity of 280 mg $CaCO_3$ /L, the 90th percentile copper levels exceeded 1.63 mg/L [61]. However, the data available for Cambridge Bay do not indicate any correlation between hardness, alkalinity or pH with copper release. Further investigation will be conducted in subsequent research within the community to explore this relationship.

Manganese. Health Canada's guidelines set the MAC for manganese at 120 ug/L with an AO of 20 ug/L [15]. Manganese concentrations above 20 ug/L can lead to complaints about discoloured water, staining of plumbing fixtures and laundry, and overall dissatisfaction with drinking water quality [62–65]. Additionally, there are several studies that have linked the consumption of drinking water with elevated levels of manganese to neuropsychological disorders in infants and children [66,67].

In 2017, manganese levels exceeded the MAC in the source water, treatment plant, and trucks

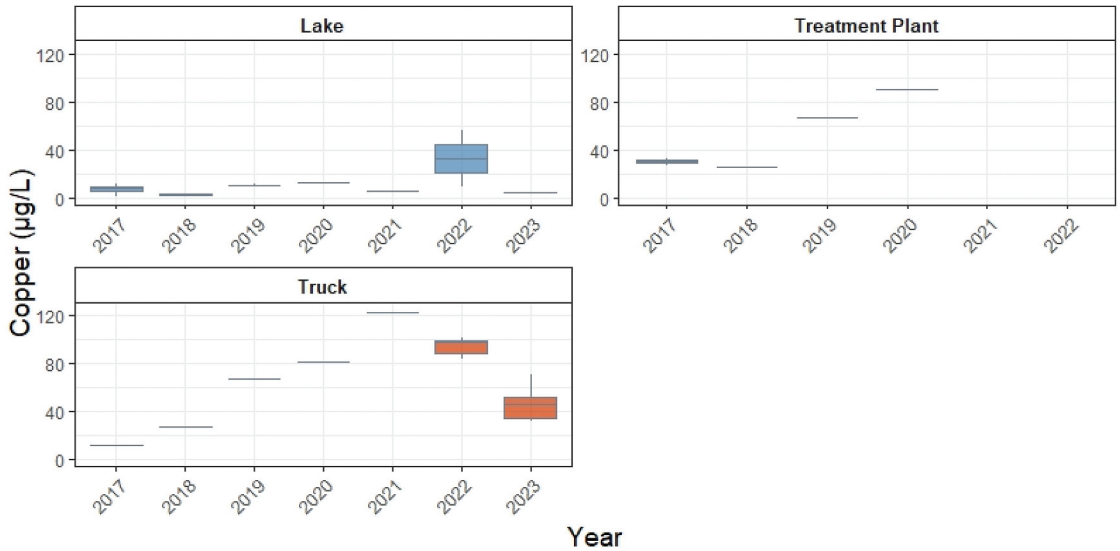

Figure 4. Copper levels within the lake, treatment plant, and trucks from sampling events during spring freshet months sample numbers for each location: lake (#13), treatment plant (#7), trucks (#18).

(Figure 5 and S3). Manganese levels in the water treatment plant and trucks were significantly lower in 2018 than in 2017, coinciding with a major upgrade to the water treatment plant including the installation of three pressure filters. Manganese remained over the AO within the treatment plant and trucks in 2018 but remained below the AO thereafter. Analysis of the 2022–2023 dataset confirmed an ongoing and statistical difference between source water and treated water (Kruskal–Wallis $p < 0.05$). This indicates that treatment plant upgrades have effectively reduced naturally occurring manganese to levels below the AO.

Other metals. Significant variations in aluminium ($p < 0.05$), iron ($p < 0.05$), and zinc ($p < 0.05$) were noted over different years (Kruskal-Wallis), indicating potential variations in general water quality across the system. Water trucks were over the operational guideline for Aluminium (0.1 mg/L) on two counts between 2017 and

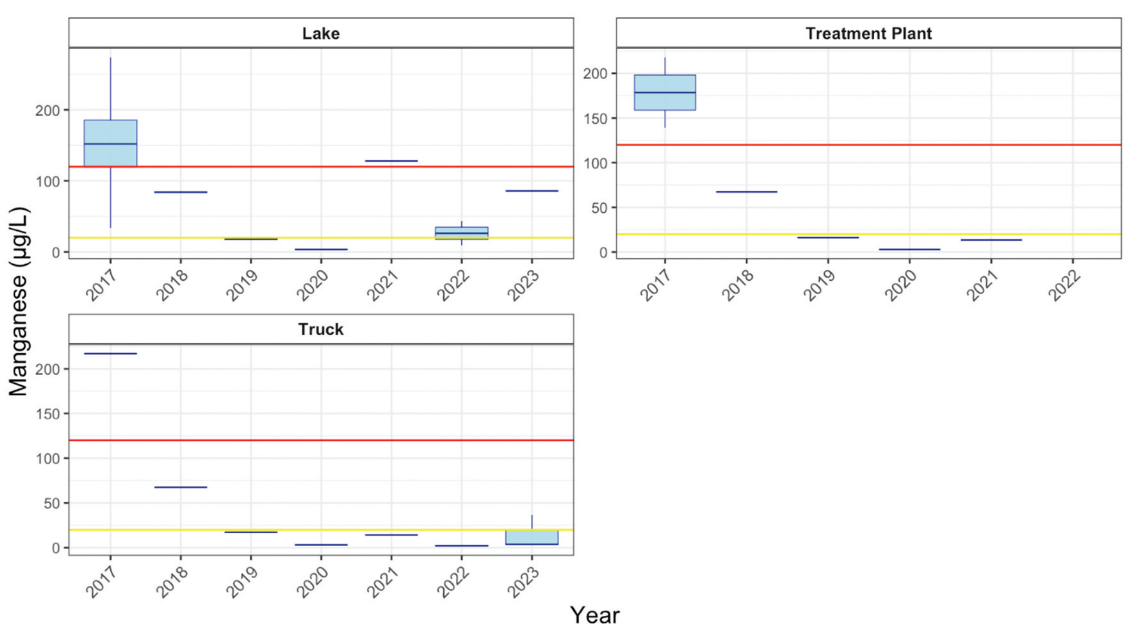

Figure 5. Manganese concentrations in the lake, treatment plant and trucks from 2017 to 2023 during spring freshet in Cambridge Bay, NU. Red line represents health Canada's MAC (0.12 mg/L) and the yellow line represents the AO (0.2 mg/L). Sample numbers for each location: lake (#13), treatment plant (#7), trucks (#18).

2023, both which were during sampling events taken during spring freshet. There is evidence to suggest seasonal trends of other water quality parameters could influence the levels of aluminium concentrations such as natural organic matter [68]. Levels of iron did not exceed the AO (100 ug/L) [14] after the treatment upgrades, there were significant differences between locations and over the years ($p < 0.05$), suggesting the upgrades was removing natural sources of iron. Similarly, zinc was found to be significantly different between locations ($p < 0.05$) and between the years ($p < 0.05$), but did not exceed the AO (5 mg/L).

Natural organic matter (NOM). NOM was measured as total organic carbon (TOC) and dissolved organic carbon (DOC) during each sampling event from 2017 to 2023 in all locations. Significant differences were observed for TOC ($p < 0.05$), among locations (ANOVA), and DOC ($p < 0.05$) over different years (Kruskal-Wallis). In the source water, ANOVA analysis showed significant differences in DOC and TOC (all $p < 0.05$) over the years.

Cambridge Bay's DOC results during spring freshet ranges from 7.2 to 9.5 mg/l depending on the year (Figure 6, Table S3). This range of DOC is consistent throughout the system, which is the be expected since the coagulant system is offline and thus there is no treatment for NOM removal. NOM, left in water can lead to THM levels surpassing recommended guideline limits, and will also increase chlorine demand reducing disinfection effectiveness even with dosages aimed at achieving 4-log removal for viruses [54].

Beginning in 2022, sampling was carried out on all trucks for physical and chemical water quality parameters. The dataset contains data points from March and June which are the start and end of spring freshet (Figure 7). Within the trucks, DOC was significantly different in the sampling events June 22 and September 22 ($p < 0.05$) indicating a seasonal variation in DOC. There is a wide range of DOC values measured during sampling events in the trucks in 2022 (5.60 mg/L in September and 9.20 mg/L in June). This variation can also be seen in the source water, indicating that the treatment processes in the plant are not removing DOC. ANOVA analysis revealed significant differences in DOC ($p < 0.05$) and TOC ($p < 0.05$) in the source water between sampling events. In June 2023 the sampling point was taken from the surface of the lake rather than where the intake draws water from, providing an outlier in the data, this data point was removed.

UV transmittance (UVT) is commonly measured ahead of UV disinfection systems to ensure that an adequate amount of UV light can travel through the water to inactivate the target microorganisms. UVT is usually measured and reported at 254 nm, which is the wavelength emitted by low-pressure UV lamps. UVT is also widely used as a measure of NOM in drinking water because aromatic NOM compounds like humic and fulvic acids absorb UV light [67]. UVT measurements only began in September 2022 and measured values ranged between 79% and 91%, with three out of four sampling events not meeting the minimum UVT requirement of the UV disinfection

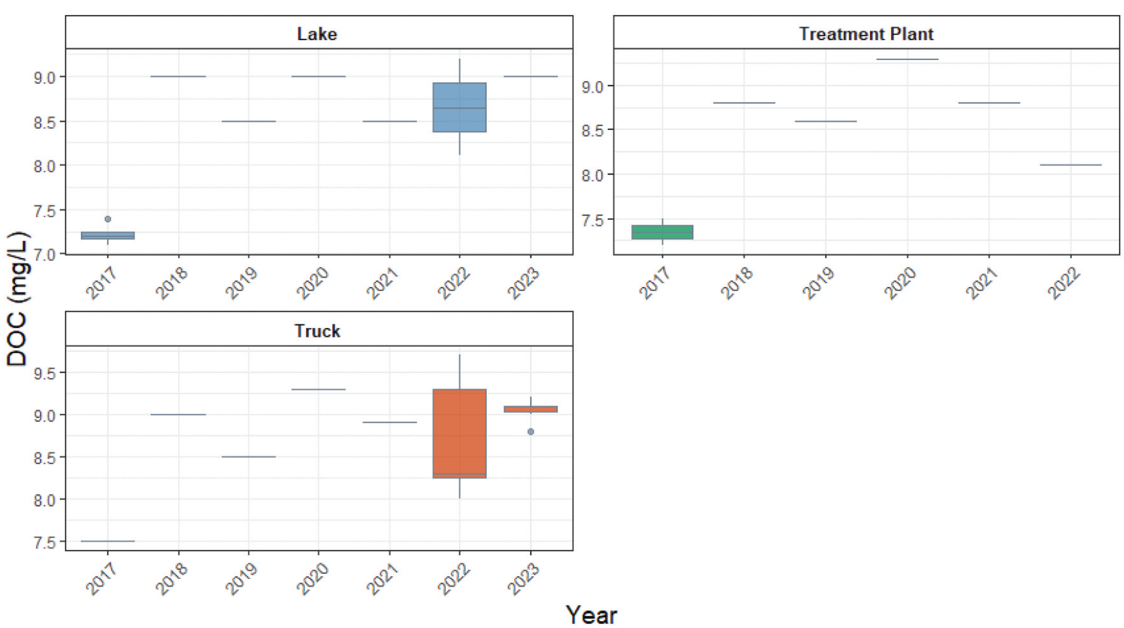

Figure 6. Dissolved organic carbon levels in the lake, treatment plant and truck in Cambridge Bay, NU. No removal of NOM from treatment plant.

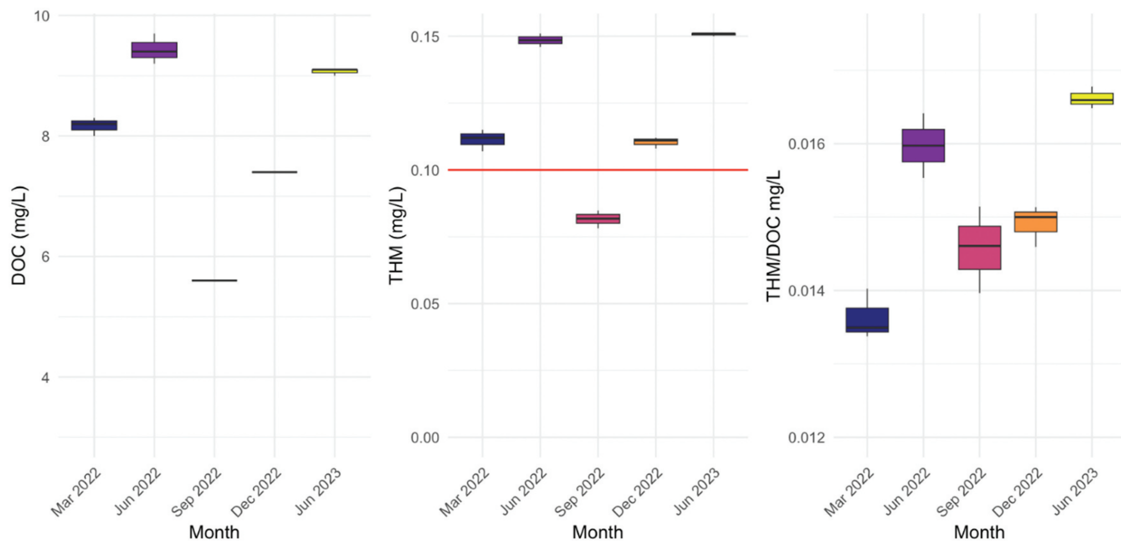

Figure 7. Left – DOC within each truck during sampling events in Cambridge Bay, NU. Middle - THMs within each truck during different sampling events red line indicates Health Canada's recommended MAC for THMs in drinking water (0.1 mg/L) [24]. Right - THM over DOC from March 2022 to June 2023 from samples taken from the water trucks.

system of 85%. UVT was converted to UV_{254} to determine the specific ultraviolet absorbance. All sampling events were below 2 L mg^{-1} m^{-1}, indicating there may be challenges removing NOM through enhanced coagulation should the system be brought back online [26][].

Disinfection byproducts. DBP formation is a function of three factors: Chlorine dose, holding time, and the characteristics of the organic matter present in the water [69,70]. Cambridge Bay does not record the chlorine dosage. Instead, the chlorine feed rate is changed daily to maintain a free residual of roughly 1 mg/L in the treated water tank prior to entering the truck fill. The free chlorine residual is monitored in the trucks after they are filled (Figure S.3) and historical data indicate that at this stage free chlorine ranges from below detection (0.02 mg/L) to 2.1 mg/L and an average of 0.48 mg/L from 2017 to 2023, with many measurements below the limit of detection of the instrument used for analysis.

Figure 7 shows the concentrations of DOC and THMs recorded within the water trucks from 2022 to 2023. The concentration of THMs was also normalised by DOC (THM/DOC), an approach widely used in applied drinking water treatment studies to provide rough information about the propensity of the organic matter present during a given sampling event to interact with chlorine to form THMs [71]. There was a statistically significant difference between sampling events for DOC, THMs, and THM/DOC ($p < 0.05$), which indicates a potential for a seasonal influence on the levels of these parameters (e.g. THMs were 70–80 ug/L in Sept 2022, and 150 ug/L in June 2023).The results suggest that the quantity of DOC appears to have had a stronger influence on THM formation compared to the NOM's reactivity towards chlorine as measured by THM/DOC, i.e. the humic content of the water (Figure 7). For example, March 2022 had DOC levels of 8.0–8.3 mg/L, but the THM/DOC was lowest of all sampling events (0.0135–0.014 mg/L). This period corresponded with THMs exceeding the MAC. Further investigation is required to comprehend the dynamics of THM formation and DOC in Cambridge Bay, which may influence the treatment of the source water.

Correlations among different water quality parameters

Spearman's correlation analysis was conducted to examine relationships between water quality parameters. Clear relationships were observed (Table S7), particularly between the formation of THMs and DOC levels with a strong correlation ($\rho > 0.90$) in the 2022–2023 dataset.

DOC and THMs. The formation of THMs is a result of chlorine disinfectants reacting with organic matter [24]. Figure 9 illustrates a distinct relationship between the formation of THMs and DOC. However, likely due to the inconsistent sampling performed between 2017 and 2023, our analysis of seasonal trends was inconclusive.

TOC and copper. There is evidence suggesting that NOM can facilitate copper leaching [18]. Arnold et al., (2012) found that a TOC reduction to 0.25 mg/L was required to sufficiently control copper release which was consistent with other researchers [72–75].

There was no statistical relationship between TOC and copper release within the trucks. Sampling techniques can vary from project to project, depending on the knowledge and training provided to operators. From the authors' experience working with water operators in Nunavut, it is common practice for the operators to take samples directly from the truck hose without flushing. Samples taken can be considered grab samples. Copper showed an unusual trend within the trucks (Figure 4 and S1) with a significant difference between March 2022 and September 2022 (ρ <0.05) and June 2022 and September 2022 (ρ <0.05). However, copper release within the trucks decreased over time (Figure S1).

Copper and zinc. There was a strong correlation between copper and zinc within the 2022–2023 truck samples ($\rho > 0.85$) and a moderate correlation between zinc and iron ($\rho > 0.54$) (Table S7). It is currently unknown if there are some brass fittings within the water trucks. Although levels found within the trucks are not considered elevated, these strong correlations between copper, iron and zinc suggest that corrosive activity is occurring [76]. Further testing is needed to determine the cause and consequence of the potential corrosion.

Summary of water quality hazards identified in the historical water quality data. The analysis of Cambridge Bay's historical water quality data identified four major water quality hazards in the community:

- Seasonal DOC elevation in source water that reaches levels that may decrease the effectiveness of treatment and promote DBP formation (not currently controlled by treatment)
- Seasonal elevation of manganese in source water (currently controlled by treatment)
- THM exceedances in delivery trucks
- The copper-zinc relationship suggests corrosion of metallic components in trucks and in building plumbing systems.

Evaluating water safety risks in Cambridge Bay using the proposed water safety framework for Nunavut

This paper follows through on steps 2–4 of the framework proposed in [2]. Three of the hazards were selected from the water quality analysis and two hazards that have occurred in Cambridge Bay are selected from Table 1.

Hazard 1: THMs in trucked water. At present THMs are monitored quarterly in water delivery trucks, giving a past frequency score of 2. The water treatment plant has no barriers to remove THMs, so the hazard receives a system readiness score of 4. Due to the association of THMs with carcinogens, this scenario receives a consequence score of 4 for potential chronic illness from long-term exposure. When first upgraded in 2017, the system in Cambridge Bay included ferric chloride coagulation; however, due to corrosion issues coagulation was stopped to maintain the integrity of the treatment plant. GN-CGS has hired a consultant to plan the reintroduction of coagulation for NOM removal, as reducing chlorine dosing is not a viable strategy for DBP while maintaining chlorine residual levels. Until the proposed recommendation from the consultant is implemented the THMs in trucked water will remain high risk with a score of 16 (RE1) or 14 (RE2).

Hazard 2: copper in tap water. For hazard 2, a past frequency score of 1 was given because two non-routine samples taken in 2017 at Kiilinik High School had copper levels close to the MAC. Corrosion causing copper to leach into drinking water from pipes is not being monitored in the community and there is little information available because water quality testing in buildings is not a regulatory requirement. The high school has water filtration stations which could be offering a sufficient barrier; however, it is unlikely that the same level of filtration is available in individual dwellings and other community buildings. As a result, a score of 5 was given for system readiness. As copper levels are only above the AO (1000 ug/L) a consequence score of 2 has been given [18]. There is insufficient data to inform risk mitigation within the community. However, a small sampling campaign that took place in 2024 by the first author to identify where the corrosion issues are likely to be occurred, that included sampling in the high school. The results will determine if the consequence can remain at a score of 2 or needs to be increased. As there is no ongoing monitoring nor barriers in place for copper levels exceeding the AO in tap water, this risk will remain moderate with a score of 10 (RE1) or 8 (RE2).

Hazard 3: hydrocarbons in source water due to fuel spill. The hazard received a score of moderate as once identified that a fuel leak from the generator was occurring, the fuel storage was moved to meet the minimum distance from the water source and placed within a bund wall. The past frequency score for hazard 3 was 1 as it occurred in the last 5 years. As interventions have already occurred, as mentioned above, the system readiness score given was a 2. Additionally, monitoring of hydrocarbon takes place 4 times a year within the source water and there have been no exceedances. If the source water were to become contaminated, the community would require identifying an alternative source for water deliveries to continue, while the source water and treatment plant is cleaned up. The consequence score is therefore a 5. This hazard is considered a moderate risk of 10 (RE1) and 8.75 (RE2).

Hazard 4: manganese in tap water. Prior to the treatment plant upgrades, manganese levels in the treated water were above the MAC (120 ug/L). In 2018 after the new WTP was commissioned, the concentration of manganese in the treated water was brought below the MAC and then further reduced to levels below the AO (20 µg/L). A past frequency score of 1 has been assigned as an exceedance has occurred at least once in the last 5 years. Current treatment includes pre-chlorination which oxidises manganese before water enters the pressure filters, acting as a barrier resulting in a system readiness score of 2. If the barriers were to fail, depending on the season, the highest consequence level would be a 4, as it is possible that manganese levels would be over the MAC. This hazard is of moderate risk of 8 (RE1) and 7 (RE2).

Hazard 5: inadequate water delivered to cisterns due to breakdown of truck. Water trucks in Nunavut undergo stress from unfavourable road conditions and extreme temperatures. Water trucks are often run until they fail which time they are placed into the municipal garage to await repairs for weeks or months, interrupting delivery. This has occurred on numerous occasions in Cambridge Bay in the last 5 years. This hazard received a past frequency score of 2. There is no preventative maintenance, only storage in a garage to reduce the impacts from weathering and vandalism. As no parts are readily available for repairs, should there be one or more trucks out of commission for extensive periods of time this would significantly reduce water delivery. Therefore, a system readiness score of 4 was assigned. A consequence score of 3 was assigned, as a reduction in consumption and hygiene is anticipated based on a previous study in Coral Harbour, Nunavut [55]. This hazard is considered high risk with a 12 (RE1) and moderate in RE2 (10.5).

Table 2 presents the risk scores and levels for both equations. The risk score calculated with RE1 (no past frequency) is always higher than that predicted with RE2 (includes past frequency). Unless past frequency scores are high (≥4), the risk level assigned to the hazards decrease, potentially diminishing the true risk level for the hazard. No hazards reviewed in this paper had a high past frequency score. As previously stated, Cambridge Bay has one of the more comprehensive water quality datasets in Nunavut, but important gaps remain, including information about the occurrences of pathogens such as *Cryptosporidium and Giardia* in source water, a hazard previously identified in Iqaluit [6]. If risk equations were applied in other Nunavut communities, the past frequency score could hinder the true risk scores and levels. Instead, past evidence that something has occurred in some part of the territory (see master list in [2] and Table 2) could be used to develop a template of potential hazards that should be assessed in all communities. Each hazard/hazardous event can be evaluated based on whether a barrier exists for it [77].

Ultimately, the WSP water safety risk matrix approach can only realistically be used to assess discrete hazards/hazardous events that have been recorded in the territory and does not meaningfully engage with the complexity of the governance, climate, and logistical context in Nunavut. New approaches that engage with the system on many levels – design, monitoring, operation, and a wide range of stakeholders, are required to understand and improve water safety in the territory. To improve public health through risk management and optimise operations, the facilitation of the WSP approach needs to be community-specific, collaborative, and iterative. Despite the advantages, however, this approach will impose continuing time demands on community members and other participating stakeholders and will be expensive, which could hinder its adoption, especially over the long term. One potential way to increase potential adoption is through the use of participatory system dynamics. Recent policy changes like the Nunavut Drinking Water Strategic Framework [48] and the Drinking Water Action Plan (C. Duncan, personal communication) will support the development of rigorous and appropriate water safety management approaches in the territory. The Drinking Water Action Plan is a direct outcome from the strategic framework, and will include all the stakeholders that were identified in the framework to create and deliver the action plan.

Conclusions and recommendations

The primary objective of this study, to conduct a case study on the application of a Nunavut specific framework for water safety management and water safety risk matrices in Cambridge Bay, NU was achieved. The secondary objective of characterising temporal and location-based trends was only partially met because of a lack of available water quality data. This work serves as a foundational study for understanding water quality and water safety risk in Cambridge Bay, highlighting areas that need attention and further research. Design and operational records and historical water quality datasets provided by the Government of Nunavut were used to assess a selection of water safety hazards including metals (copper and manganese) and organics (dissolved organic carbon, disinfection byproducts). With minor exceptions, this dataset represents water from the source, the treatment facility, and within the trucked distribution system. These data established the past frequency score for the selected hazard using the Nunavut water safety risk matrix.

Since upgrading the treatment plant the community is now maintaining levels below both the MAC and AO for manganese and the AO for iron. Copper levels were above the AO localised to tap water, indicating potential plumbing corrosion occurring in buildings. The use of copper pipes could also be an indicator for lead. Lead solder historically has been used in buildings in Nunavut identified in previous studies and could be potentially another hazard to consider [11]. The quantity of NOM during spring freshet, as opposed to the composition of NOM, appears to be the driving factor for THM formation (Figures 7 and 8).

This case study is the first to trial the Nunavut-specific WSP framework proposed by [2]. Although Chalmers et al. (2025) identified that inclusion of past frequency in the risk equation increased the ability to leverage past data, this case study demonstrated that its inclusion reduced the overall risk score even if system readiness score and consequence scores were high. This is because official past records are extremely limited, resulting in most hazards being assigned low scores for past frequency and consequently low overall risk scores. Therefore, RE1, which only considers whether effective barriers are present to prevent the risk of a hazard impacting the community, is preferred for use in the territory.

Suggestions for future research in Cambridge Bay, NU and other Arctic communities include:

- Conduct comprehensive metals testing in various community buildings, including municipal and residential buildings, using different sampling techniques to provide more accurate information on distribution/plumbing water quality,
- Assess and explore potential solutions to improve the water quality in cisterns and explore potential solutions to improve water quality in cisterns,
- Collaboratively assess culturally significant alternative water sources and storage methods outside the municipal system to support community awareness of water quality,
- Collaborate with communities to develop WSPs, thus enhancing community understanding of the watershed, water systems, and home-based strategies to reduce contamination risk. This will require buy-in from operational staff, community members and local organisations and regulators to support a WSP approach.

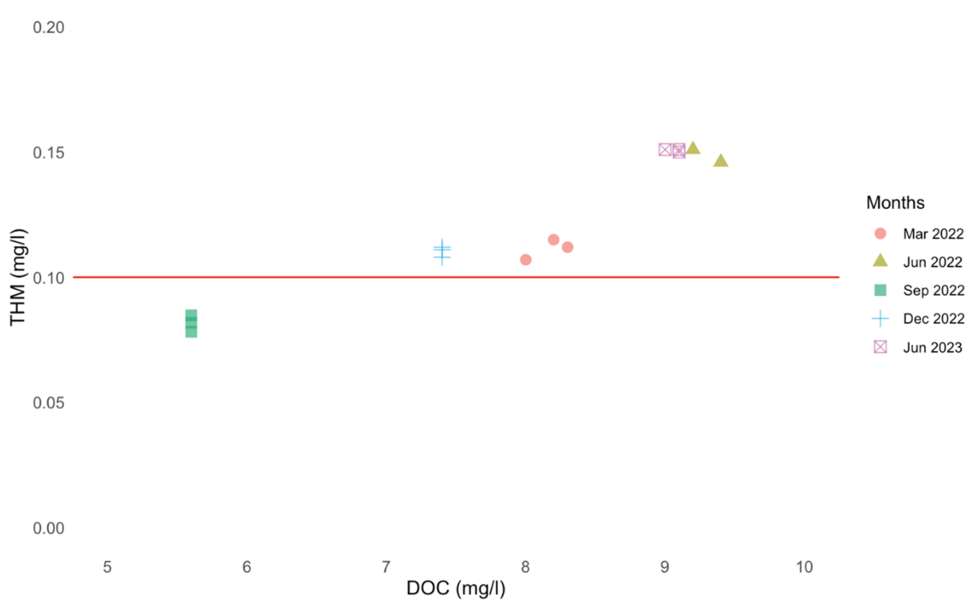

Figure 8. Correlation of DOC and THMs in Cambridge Bay, NU. The red line represents the maximum allowable concentration of THMs of 0.1 mg/L [24].

Finally, there remains a pressing need to better grasp and incorporate the social, cultural, and economic factors influencing drinking water safety conditions in remote communities, especially those serving vulnerable populations [55,78–80]. Future research by the first author intends to tackle this through participatory research using system dynamics with community members and drinking water stakeholders in the Territory.

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Disclosure statement

No potential conflict of interest was reported by the author(s).

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Ethics

This research was conducted under Ethics certificate: 2024–004 from York University Ethics Review Board and Nunavut Research License: 04 001 24N-A.

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